63-3-3

SSD-TDR-63-44

REPORT NO.
TDR-169(3230-12)

Aeromechanics Program

Heat Transfer and Fluid Mechanics

SEMIANNUAL TECHNICAL REPORT

(1 July – 31 December 1962)

28 FEBRUARY 1963

Prepared by P. M. CHUNG, W. S. LEWELLEN, and D. J. SPENCER
Aerodynamics and Propulsion Research Laboratory

Prepared for COMMANDER SPACE SYSTEMS DIVISION

UNITED STATES AIR FORCE

Inglewood, California

LABORATORIES DIVISION • AEROSPACE CORPORATION

CONTRACT NO. AF 04(695)-169

SSD-TDR-63-44

Report No.
TDR-169(3230-12)TR-2

AEROMECHANICS PROGRAM

Heat Transfer and Fluid Mechanics

SEMIANNUAL TECHNICAL REPORT
(1 July - 31 December 1962)

Prepared by

P. M. Chung, W. S. Lewellen, and D. J. Spencer
Aerodynamics and Propulsion Research Laboratory

AEROSPACE CORPORATION
El Segundo, California

Contract No. AF 04(695)-169

28 February 1963

Prepared for

COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

ABSTRACT

This report covers the major areas of: Heat Transfer, Fluid Mechanics, and Arc Tunnel Facilities. Studies of the effect of various distributions of surface catalycity on heat transfer for frozen boundary layer flows of dissociated gas around hypersonic bodies are summarized. The fluid dynamics investigations include summaries of studies of expansion of gas clouds, three-dimensional boundary layers, electrical interactions of weakly ionized gas with solid boundaries, vortex flows, test time in shock tubes, and secondary injection for thrust vector control. Arc tunnel facility improvements include completion of the high capacity pumping system, implementation of the constant power control system, and design of an improved test section and model/probe support mechanism.

CONTENTS

FIGURES

PREFACE

The work carried out under JO 3230-12 has, for convenience, been divided into three major subject areas: Heat Transfer, Fluid Mechanics, and Arc Tunnel Facilities. This report reflects these three categories; individual editors have compiled the major sections, each of which is a separate entity.

Because the studies conducted under this JO are often short-term and not related to other major program efforts, technical plans are included in this report only where applicable.

I. HEAT TRANSFER
(P. M. Chung)

A. INTRODUCTION

Theoretical and experimental research has been conducted on the effects of non-equilibrium surface and gas-phase chemical reactions on heat transfer. Understanding these effects is essential to evaluate heat transfer to hypersonic vehicles, and to design ablators for non-ballistic re-entry space vehicles. The study is also important for chemical diagnostics in high temperature experimental facilities such as arc and shock tunnels.

B. THEORETICAL WORK ON CHEMICALLY REACTING AIR BOUNDARY LAYERS

Previous analyses of non-equilibrium boundary layers showed that for many flight conditions of hypersonic vehicles and for an extensive regime of test conditions in high temperature experimental facilities, the gas-phase chemical reaction (recombination of dissociated atoms) is nearly frozen. A study was, therefore, made of the effect of various distributions of surface catalycity on the heat transfer for the frozen boundary layer flows of dissociated gas around hypersonic bodies.

Although catalytic surface recombination in the boundary layer flow of frozen dissociated gas has been analyzed extensively, the analyses were limited to cases in which the surface catalytic efficiency was invariant. In practice, however, the catalytic efficiency of the surface varies in some arbitrary manner due either to the variation of surface temperature or of the surface material. With a continuous variation of surface temperature, the catalytic efficiency varies continuously; when the surface is made of different materials located adjacently, the catalytic efficiency has a discontinuous variation.

Reference I-1 presents methods for solving discontinuous variations of surface catalytic efficiency. Two of the more important applications of this analysis are:

1. Noncatalytic Surface Materials

A noncatalytic surface material may be used to reduce the maximum local heat transfer (e. g. , near a leading edge or a stagnation point). Reference I-1 describes the effect of the upstream surface's chemical condition on heat transfer to the downstream surface when the catalytic efficiency of the two surfaces is different.

2. Catalytic Gage Construction

This application is associated with construction of catalytic gages for the diagnostics (measurement of local atom concentration) of high-temperature experimental facilities. The analysis shows that, in most cases: (a) the catalytic gage surfaces should be located away from a leading edge or a stagnation point, and (b) a noncatalytic material should be used for the surfaces upstream of the gage surfaces. The free stream concentration of dissociated atoms can be derived from gage surface heat transfer data presented in Ref. I-1.

A subsequent report (Ref. I-2) presents a more general form for determining the catalytic efficiency of continuous, as well as discontinuous, surface variations.

No general solution of the boundary layer equations is available which considers simultaneous non-equilibrium gas-phase and surface chemical reactions. An approximate closed form solution was obtained (Ref. I-3) which gives the simultaneous chemical effect on the heat transfer to the stagnation region of axisymmetric bodies.

C. THEORETICAL AND EXPERIMENTAL WORK ON ABLATION

Several new ablation problems associated with lifting re-entry trajectories have been investigated. Thermal and chemical responses within an ablating material, in general, are not steady and can progress at markedly different rates from that at which the heat addition surface recedes. The prediction of thermal protection capabilities and required thicknesses of heat shields for specific trajectories can be accomplished by the simultaneous solution of energy equations for the gas boundary-layer and the ablating material. These energy equations are written in forms suitable for computer solutions (Ref. I-4) for one-dimensional heat transfer. Solutions for specified trajectories have been obtained using an analog computer. A satisfactory check has been obtained in which the results were compared for purely thermal (no recession or pyrolysis) response against an existing, proven, computer program for transient heating.

Assistance has been rendered to other Aerospace Corporation groups engaged in the assembly of a digital computer program for transient ablation. This new program (currently in the final checkout stages) has a wide variety of options for insertion of material properties and surface heat-transfer and mass-transfer relations, and is based on the energy equations derived earlier for the analog computer. Because of the requirements for a large information storage capability and a large number of spatial nodes, a digital computer is preferable to an analog computer for this problem.

Two series of experimental ablation tests were performed on a particular material at low heat-transfer rates, in conjunction with a design feasibility study performed by the Engineering Division. These tests were performed in the subsonic and supersonic portions of the 200 kw plasma arc.

The combustion rate of the charred layer formed by a degraded plastic ablation material is an important aspect of the transient ablation problem because it regulates the heat input to the solid and determines the dimensional change

of the solid during re-entry. For several reasons, it is more convenient to study the combustion phenomena using a more homogeneous carbon such as graphite rather than a charred layer of degraded plastic.

The combustion of graphite in oxygen has been studied for many years in conjunction with the development of engineering processes utilizing solid fuels as a heat source. Some general aspects of the problem are well understood, but many important details are in question. At high surface temperatures, the combustion rate is limited to that corresponding to the rate at which oxygen can be diffused through the boundary layer to the surface. At low surface temperatures the combustion proceeds at a rate controlled by chemical kinetics, the details of which vary somewhat for different types of graphite. Oxygen diffusion rates may, in principle, be calculated using available boundary layer methods. In practice, this has not been accomplished with a high degree of accuracy, particularly for complex geometries. The chemical kinetics, however, are not amenable to a priori calculation because of uncertainties in the choice of the appropriate rate-controlling process and the effects of porosity and impurities. Thus, empirical data correlations are commonly used to describe the kinetics.

To demonstrate the interaction of the effects of oxygen diffusion and surface kinetics at intermediate surface temperatures, an analysis was performed of the combustion rate of graphite at the stagnation surface of a re-entry vehicle using available, simplified, relations for diffusion and kinetic effects (Ref. I-5). A Damkohler number was defined as the ratio of the characteristic diffusion time to the characteristic reaction time. This parameter allowed a simple, general solution of the problem for any specification of chemical kinetics. Experimental tests were performed on the combustion rate of a common grade of graphite, type ATJ, using a subsonic plasma jet from the 200 kw arc. The results in the intermediate temperature range are in good correspondence to the theory. Analytical and experimental efforts were

initiated on another interaction (which may be significant at higher surface temperatures) between the effects of heterogeneous reaction kinetics and the wall-catalyzed homogeneous equilibrium between carbon dioxide and its dissociated forms. If this higher temperature interaction is verified, several significant questions concerning carbon combustion may be answered, of which the ratio of carbon monoxide to carbon dioxide produced by the heterogeneous reaction is the most important.

D. REFERENCES

I-1. Chung, P. M., S. W. Liu, and H. Mirels, "Effect of Discontinuity of Surface Catalycity on Boundary Layer Flow of Dissociated Gas", Aerospace Report TDR-69(2240-20)TN-1, 7 June 1962.

I-2. Liu, S. W. and P. M. Chung, "Boundary Layer Flow of Dissociated Gas with Arbitrary Distribution of Surface Catalycity", Aerospace Report (to be published).

I-3. Chung, P. M. and S. W. Liu, "An Approximate Analysis of Simultaneous Gas-Phase and Surface Atom Recombination for Stagnation Boundary Layer", Aerospace Report TDR-169(3230-12)TN-4, 26 November 1962.

I-4. Lafazan, S. and W. E. Welsh, "The Charring Ablator Concept-Application to Superorbital Reentry", Aerospace Report (to be published), also presented at 1962 AFOSR Conference on Reentry Problems, Philadelphia, Pennsylvania, November 1962.

I-5. Welsh, W. E. and P. M. Chung, "An Analysis of the Effects of Heterogeneous Reaction Kinetics on the Combustion Rate of a Graphite Stagnation Surface in Hypersonic Flow", Aerospace Report TDR-169(3230-12)TN-6, 28 February 1963.

II. FLUID MECHANICS
(W. S. Lewellen)

A. INTRODUCTION

A variety of investigations in the field of fluid dynamics were conducted under this program, resulting in the publication of 7 technical reports (Ref. II-1 through II-7). Consequently, this summary is divided into 7 sections, corresponding to the subject areas investigated in each report.

B. EXPANSION OF GAS CLOUDS

The fluid dynamics of explosions, of pulsed accelerators, and of hypersonic rockets in space has recently become a problem of considerable importance. For this reason the unsteady expansion of gas clouds, bounded by vacuum, was investigated (Ref. II-1) for both continuum and free molecular flows.

The known analytical solutions from similarity theory, plane continuum flow, and free molecular flow were reviewed with emphasis on the asymptotic nature of the flow after long times; it was found that all have a similar form in this limit. An approximate analytical solution (which is exact in the plane case) was presented for a continuum expansion, after long time, of an initially uniform gas cloud. For cylindrical and spherical expansions, the approximate solution gave results for density (at the axis) which were higher than those obtained by a numerical integration of the equations, the best agreement being found for the cylindrical case and small ratio of specific heats.

The continuum and free molecular expansions of an initially uniform gas were found to be quite similar, after long time, except for flow in the vicinity of the leading edge of the expansion (there is no leading edge in the free molecular flow case). For a given gas, the density at the axis decays more rapidly with time for the continuum case.

Using the hypersonic-equivalence principle, these results were extended to hypersonic jets bounded by vacuum. In this case, where the specific heat ratio of interest is about 1.2, the results are expected to be valid to within 10 percent.

C. THREE-DIMENSIONAL BOUNDARY LAYERS

The majority of work in boundary layer theory has been concerned with two-dimensional (plane) flows in which only one velocity component outside the boundary layer enters into consideration. In three-dimensional boundary layer flows there is generally one more velocity component both within and at the outer edge of the boundary layer. The problem contains one more unknown which is accompanied by one additional momentum equation. Most of the extensions to three dimensions were made on the premise that a single similarity variable can be used for both components of the boundary layer flow. With more than one velocity component in the outer flow field, the question arises as to which velocity component should be adopted to formulate the similarity variable if only one such variable is to be used throughout the problem. The use of the same similarity variable on both flow components requires some justification which, in many cases, may not be readily obvious. In fact, many such solutions gave inconsistent results when carried to the limit where the second flow component became the dominating one in the problem.

A new approach to three-dimensional boundary layer problems was therefore proposed (Ref. II-2). The similarity concept was generalized for three-dimensional laminar flows whenever more than one velocity component exists in the inviscid flow field immediately outside the boundary layer. For each boundary layer flow component, separate similarity variables appropriate to the nature of the corresponding inviscid velocity component at the outer edge were established. For the purpose of solving simultaneous differential equations, a single independent variable was adopted as a mathematical convenience.

Two examples of immediate practical interest were chosen, for which derivations were presented for compressible flow using the proposed approach: (1) the general blunt-body stagnation point flow, and (2) the stagnation line flow of a supersonic cone at angle of attack. The examples demonstrated that consistent formulation can be obtained without the restriction of a single similarity variable. (By comparison, formulation of the same problems based on a single similarity variable is constrained to the flow component upon which the similarity is based, and such formulations are consistent only when this component is the predominant one of the problem.) The present formulation, when applicable, is therefore expected to produce results of more general validity in three-dimensional flow problems.

D. ELECTRICAL INTERACTION OF WEAKLY IONIZED GAS WITH SOLID BOUNDARY

The high-temperature gas of current interest (whether it exists in the shock layer of a hypersonic vehicle, in an arc, or in a shock tunnel of a laboratory) is usually in a partially ionized state. As the ionized gas flows over a solid boundary, an electrical interaction between the gas and the solid is observed in addition to the conventional interaction of momentum and energy. An understanding of this electrical interaction is important for hypersonic vehicles because it influences the electrical behavior of the ionized gas flowing adjacent to the body. For laboratory problems, the plasma-solid interaction is of interest because this phenomenon can be used for diagnostics of the electric properties of the gas stream.

An analysis was made (Ref. II-3) of electrical phenomena associated with the viscous compressible flow of a weakly ionized gas in which the range of electrical effects is much greater than the gas mean free path. The study began with the Couette flow model, because it is simple and yet contains many of the fundamental flow characteristics of a boundary layer. The study

was extended to the stagnation point boundary layer for two-dimensional and axisymmetric blunt bodies. The fluid was considered to be a monatomic gas, such as argon, which is weakly and singly ionized. The gas density and the electron temperature distributions across the viscous layer were found to have a drastic effect on the electrical interactions between the plasma and the solid boundary. It was shown that the analysis can be readily used for the electrical diagnostics (such as the measurement of electron concentration and electron temperature) of high temperature experimental facilities.

E. SURFACE CHEMICAL REACTION BEHIND A STRONG MOVING SHOCK

When a strong shock advances into a stationary gas, the energy of the gas is often raised to such a level that chemical reactions occur in the flow behind the shock. In addition, when the shock is moving along a solid boundary, a heterogeneous chemical reaction can also take place between the shocked gas and the solid wall, These phenomena are of interest in connection with shock tube studies.

The following problem was analyzed in Ref. II-4. The streamwise distribution of atom concentration in the inviscid flow behind the shock was considered as an arbitrarily continuous function of the distance from the shock. The surface catalycity was considered to be arbitrary but constant. The analysis then gave the surface distribution of atoms and the heat transfer to the surface.

An immediate application of this theory is seen in the chemical diagnostics of shock tubes. To determine the dissociation level behind the moving shock, a thin plate (with surfaces of known catalytic activity) can be inserted parallel to the flow to measure the heat transfer. When the heat transfer is measured both on highly catalytic and noncatalytic surfaces, the difference can be used to obtain the atom concentration at the boundary layer edge.

Ref. II-4 gives a detailed analysis of the basic criteria involved in the application of the theory to the chemical diagnostics of shock tubes.

F. VORTEX STUDIES

A major effort of the Fluid Dynamics Section has been associated with vortex studies (described in Ref. II-14) related to the gaseous nuclear rocket. During these vortex investigations, interesting questions have arisen, which, although not directly applicable to the gaseous nuclear rocket study, are important to the general understanding of vortex flows. Many of these questions are directly applicable to important vortical flows in other areas such as: tornadoes in the field of meteorology; the Ranque-Hilsch tube in the field of temperature control; and a specific concept of a power conversion device (Ref. II-8).

Reference II-5 considered the boundary layer interaction produced by the vortical flow of a viscous, incompressible, electrically conducting fluid over a stationary disk with a magnetic field aligned with the vortex axis. The relation of this problem to both the magnetohydrodynamic vortex power generator and the hydromagnetic capacitor was discussed. A momentum integral technique was used to obtain estimates of the flow behavior over a finite disk; a similarity method was used to investigate the flow over an infinite disk. The flow outside the boundary layer was assumed to be that of a strong vortex in which the streamlines are nearly circular. It was shown that in such flows the boundary-layer development may often be purely hydrodynamical even when the flow outside the boundary layer is governed by magnetohydrodynamic effects.

Similarity solutions of rotating flows over an infinite, stationary disk are being investigated in another study. Similarity parameters have been found that reduce the boundary layer equations to ordinary differential equations when the peripheral velocity of the external flow is proportional to a power of the radius, i.e., $v \sim r^n$. However, the reduction of the governing

equations to ordinary differential equations does not ensure a solution which satisfies physical boundary conditions. In fact, it has been shown that $n = -1$ has no physical solution (Ref. II-9). The equations are presently being solved numerically on a digital computer. Solutions have been obtained for $1 > n \geq 0$ to add to the solution for $n = 1$ obtained by Bodewadt (Ref. II-10). At the same time, the similarity equations for magnetohydrodynamic flow arising from the study presented in Ref. II-5 are also being solved numerically.

In the field of meteorology, a review of the literature concerning tornadoes was conducted to determine what similarities exist between this violent vortex of nature and the vortex flow already under investigation. Disregarding the obvious difference in scale, they appear to be suprisingly similar. However, some problems unique to the tornado (e.g., the effect of condensation within the flow, and the determination of proper boundary conditions at a large radius) must be dealt with before the similarities can be exploited. These problems are currently being investigated.

To study condensation effects, it is necessary to include the energy equation in the governing equations. In investigating the energy equation for three-dimensional vortex flows with strong circulation, the phenomenon of energy separation is encountered. This phenomenon is dramatically demonstrated in the Ranque-Hilsch tube (a simple vortex tube which, when properly designed, can separate a single, high-pressure, uniform-temperature gas stream into hot and cold components). Although extensively investigated both experimentally and theoretically, no complete, generally accepted explanation for the Ranque-Hilsch effect has been obtained. The present study of the energy equation should help clarify differences in the explanations offered for this phenomenon.

G. TEST TIME IN SHOCK TUBES

In an ideal shock tube (i.e., neglecting wall effects), the separation distance between the shock and contact surface increases linearly with distance from

the diaphragm. Thus, ideally, test time can be increased by increasing the length of the low pressure section of the tube.

In an actual device, the wall boundary layer causes the separation distance to reach a limiting value and to remain constant thereafter. Consequently, increasing the length of the low pressure section does not result in increased test time once the limiting separation distance is reached. This phenomenon is very important, with regard to determining test time in low density shock tubes, since the maximum possible test time is proportional to the initial pressure in the low pressure section.

The reduction of test time in low pressure shock tubes, due to a laminar wall boundary layer, was investigated (Ref. II-6). Unlike previous studies, the variation of free stream conditions between the shock and contact surface was taken into account. It was found that, except for very strong shocks, β (a parameter defined by Roshko in Ref. II-11), is considerably larger than Roshko's estimates. Since test time is proportional to β^{-2}, previous test time estimates are too large, particularly for weak shocks. The present estimates for β appear to agree with existing experimental data to within about 10 percent for shock Mach numbers greater than 5. In other respects, the basic theory is in general agreement with Roshko's results.

The effect of a turbulent wall boundary layer on shock tube test time is now under study.

H. THRUST VECTOR CONTROL

The injection of a liquid into a rocket engine exhaust cone has been suggested as a means of thrust vector control. A theoretical investigation was first presented in Ref. II-12; however, this analysis did not present an adequate representation of the liquid-hot gas interaction. Reference II-13 showed that the pressure rise due to the mass addition predicted in Ref. II-12 may not materialize because the injected liquid not only acts as a mass source

but also as an energy sink (i. e., energy is removed from the main flow to vaporize the liquid). However a detailed analysis of this phenomenon was not presented in Ref. II-13.

An analytical study of the vaporization of a liquid layer into a hot supersonic flow was conducted (Ref. II-7) to assess the importance of this phenomenon.

Because the primary objective of this study was to determine the parameters that govern the interaction, a simple, idealized model was used which retained the essential features of the actual interaction which occurs downstream of the point of injection. It was assumed that an inert liquid is injected with small momentum into a two-dimensional, hot, supersonic stream which has no axial pressure gradient. Upon entering the primary stream, the liquid is deflected in the direction of the flow, forming a layer which flows along the wall. Evaporation was assumed to commence immediately after liquid deflection.

The liquid-hot gas interaction and the interaction of liquid with a hot wall were considered using the techniques of laminar boundary layer theory. As a result of the study, the vaporization rates and the deflection of the primary stream, due to the various interactions, were determined as a function of several liquid, wall, and free stream parameters. The vaporization rate varies linearly with the difference in the enthalpy of the primary gas and the enthalpy of the injected liquid; it is also inversely proportional to the heat of vaporization of the liquid.

If the primary stream has a net positive deflection (i. e., away from the wall), a pressure rise results from the interaction, and the thrust control side force increases. If the primary stream is to have a positive deflection: (1) the heat of vaporization should be low; (2) the wall temperature should be high enough to permit liquid evaporation due to heat transfer from the wall; and (3) the energy transfer from the primary gas should be kept to a minimum.

I. REFERENCES

II-1. Mirels, H. and J. F. Mullen, "Expansion of Gas Clouds and Hypersonic Jets Bounded by Vacuum", Aerospace Corporation Report TDR-169 (3230-12)TR-1, September 1962.

II-2. Liu, S. W., "Generalized Laminar Boundary Layer in Three-Dimensional Flow", Aerospace Corporation Report TDR-169(3230-12)TN-1, 1 September 1962.

II-3. Chung, P. M., "Electrical Characteristics of Couette and Stagnation Boundary Layer Flows of Weakly Ionized Gases", Aerospace Corporation Report TDR-169(3230-12)TN-2, 1 October 1962.

II-4. Chung, P. M., "Chemically Frozen Boundary Layer with Surface Reactions Behind a Strong Moving Shock", Aerospace Corporation Report TDR-169(3230-12)TN-3, 16 November 1962.

II-5. Lewellen, W. S. and W. S. King, "The Boundary Layer of a Conducting Vortex Flow over a Disk with an Axial Magnetic Field", Aerospace Corporation Report ATN-63(9227)-1, 7 December 1962.

II-6. Mirels, H., "Test Time in Low Pressure Shock Tubes", Aerospace Report TDR-169(3230-12)TN-5, 27 December 1962.

II-7. King, W. S., "Analysis of a Vaporizing Liquid Layer in a Rocket Nozzle", (to be published).

II-8. Lewellen, W. S. and W. R. Grabowsky, "Nuclear Space Power Systems Using Magnetohydrodynamic Vortices", ARS Journal, Vol. 32, pp. 693-700, May 1962.

II-9. Moore, F. K., "Three-Dimensional Boundary Layer Theory", Advances in Applied Mechanics, Vol. 4, pp. 160-224, Academic Press, New York, 1956.

II-10. Bödewadt, U. T., "Die Dreshtrömung uberfesten Grunde", ZAMM, Vol. 20, pp. 241-253, 1940.

II-11. Roshko, A., "On Flow Duration in Low-Pressure Shock Tubes", Physics of Fluids, Vol. 3, p. 835, 1960.

II-12. Chapkis, R. L., J. M. Wu, and A. Mager, "Approximate Analysis of Thrust Vector Control by Fluid Injection", ARS Journal, Vol. 31, No. 12, December 1961.

II-13. Broadwell, J. E., "An Analysis of the Fluid Mechanics of Secondary Injection for Thrust Vector Control (Revised)", S. T. L. Report 6120-7744-MU-000, March 1962.

II-14. Rosenzweig, M. L., "Summary of Research in Advanced Nuclear Propulsion", Semiannual Technical Report, TDR-930(2210-14)TR-1, 10 March 1962.

III. ARC TUNNEL FACILITIES
(D. J. Spencer and K. E. Starner)

A. INTRODUCTION

The Aerospace Corporation arc tunnel facilities (two 200 kw tunnels and one 2 Mw tunnel) are employed in the investigation of high enthalpy gas stream interaction with materials. The 200 kw tunnels are being used in a continuing series of materials studies (see Ref. III-1).

Checkout of the 2 Mw arc plasma generator was performed after completion of the 2 Mw arc tunnel facility. The arc generator utilized in the checkout employed a cooled copper anode and a graphite cathode. Gas was injected tangentially into the arc to provide vortex stabilization and rotation of the arc column; an axial 1000 gauss magnetic field produced additional rotation of the arc column in the conical anode. The entire system was operated successfully at ~1.4 Mw power (~6000 amps, 230 volts) and 10 atm arc chamber pressure. All four subsystems (gas supply, water supply, vacuum system, and power supply) performed satisfactorily, and were under proper control of the control console. Performance of all safety interlocks was checked and verified. The 2 Mw tunnel is now utilized as the test site for arc development studies. Development and checkout of the Gerdien arc, designed to produce a clean, heated air jet of very low contamination, are being conducted here.

Recent facility improvements include completion of the high capacity pumping system, implementation of the constant power control system, and design of an improved test section and model/probe support mechanism. Emphasis has also been given to improved calibration and diagnostic techniques.

B. FACILITY IMPROVEMENTS

1. Vacuum System

The existing pumping system used with the arc tunnel facilities was augmented with the addition of a Roots-Connersville blower. The 10 mechanical pumps

(Stokes model 412H) which previously provided the exhaust sink for the tunnels were retained to provide the necessary back-up pumping capacity for the booster. The present pumping system is shown in Figure III-1. Installation of the booster required rearrangement of the pump layout in Room 70, the vacuum pump room (see Figure III-2). A port looking directly into the blower inlet is accessible from Room 665; also, a bypass duct from the 10 mechanical pumps to Room 665 provides a lower capacity exhaust capability.

The system pumping characteristics are shown in Figure III-3. The booster pumps air nominally at 16,000 ft^3/min continuously at pressures from ~20μ up to 2 mm. At the higher pressure, the "run" time is limited to 30 minutes. The "run" duration decreases, as shown in the figure, for pressures up to 13 mm; at this level, power is removed from the motor and pumping ceases. However, the motor continues to turn due to the pressure differential maintained by the mechanical pumps. Air mass flows are plotted along the characteristic curve to indicate operating pressure levels for the various mass flows. The 200 kw arcs generally operate between the 1 and 10 gm/sec limits; the 2 Mw tunnel operates in the 10 to 100 gm/sec range.

2. Arc Power Control System

The constant power system outlined in Ref. III-1 was constructed and made operational. For constant current control, the 187 kw rectifier is brought on the line after arc initiation. An operating current level is established and the current meter relay acts to increase the rectifier output current to maintain the established level as the battery-supplied current decreases. The arc voltage relay functions to advance the cathode to maintain constant arc voltage drop.

3. Test Section

Enlargement of the vacuum pumping capacity, the requirement for long-duration testing capability, and the emphasis now given to diagnostics necessitated development of an improved test section. The increased pumping capacity resulted in an attendant increase in jet exit diameter (from 2 in.

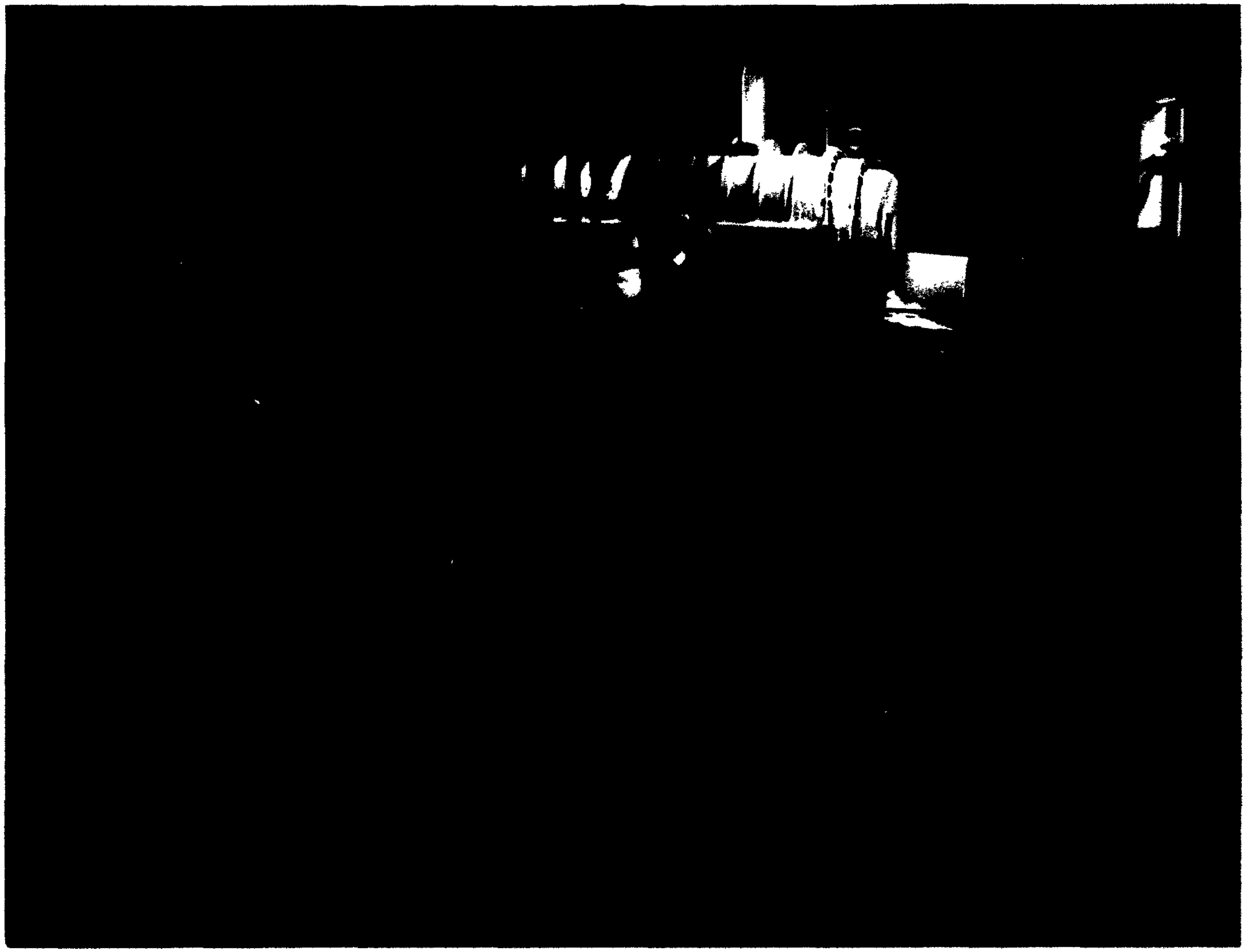

Figure III-1. Vacuum Pump Room

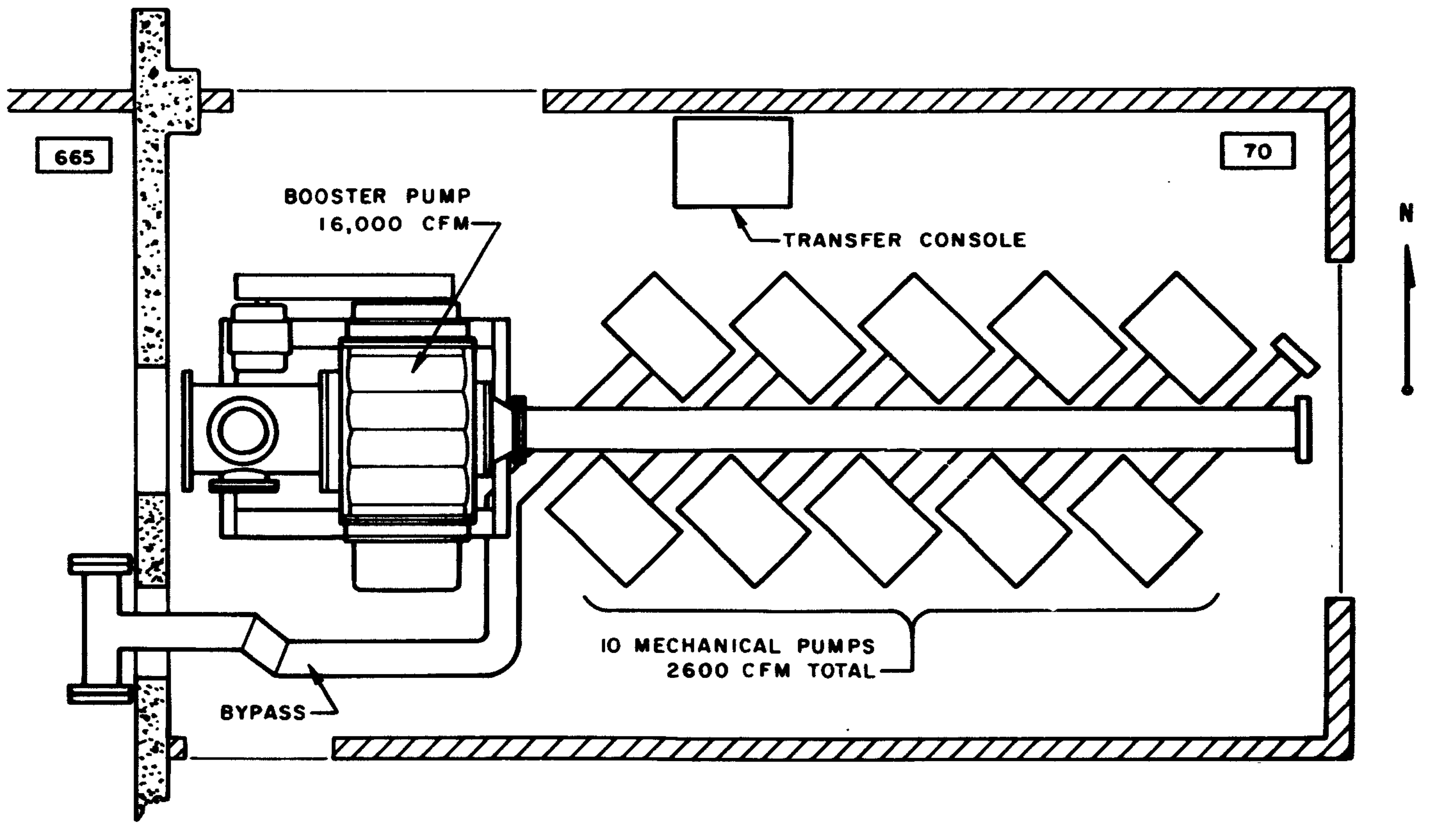

Figure III-2. Vacuum Pump Room Layout (Bldg. H-2)

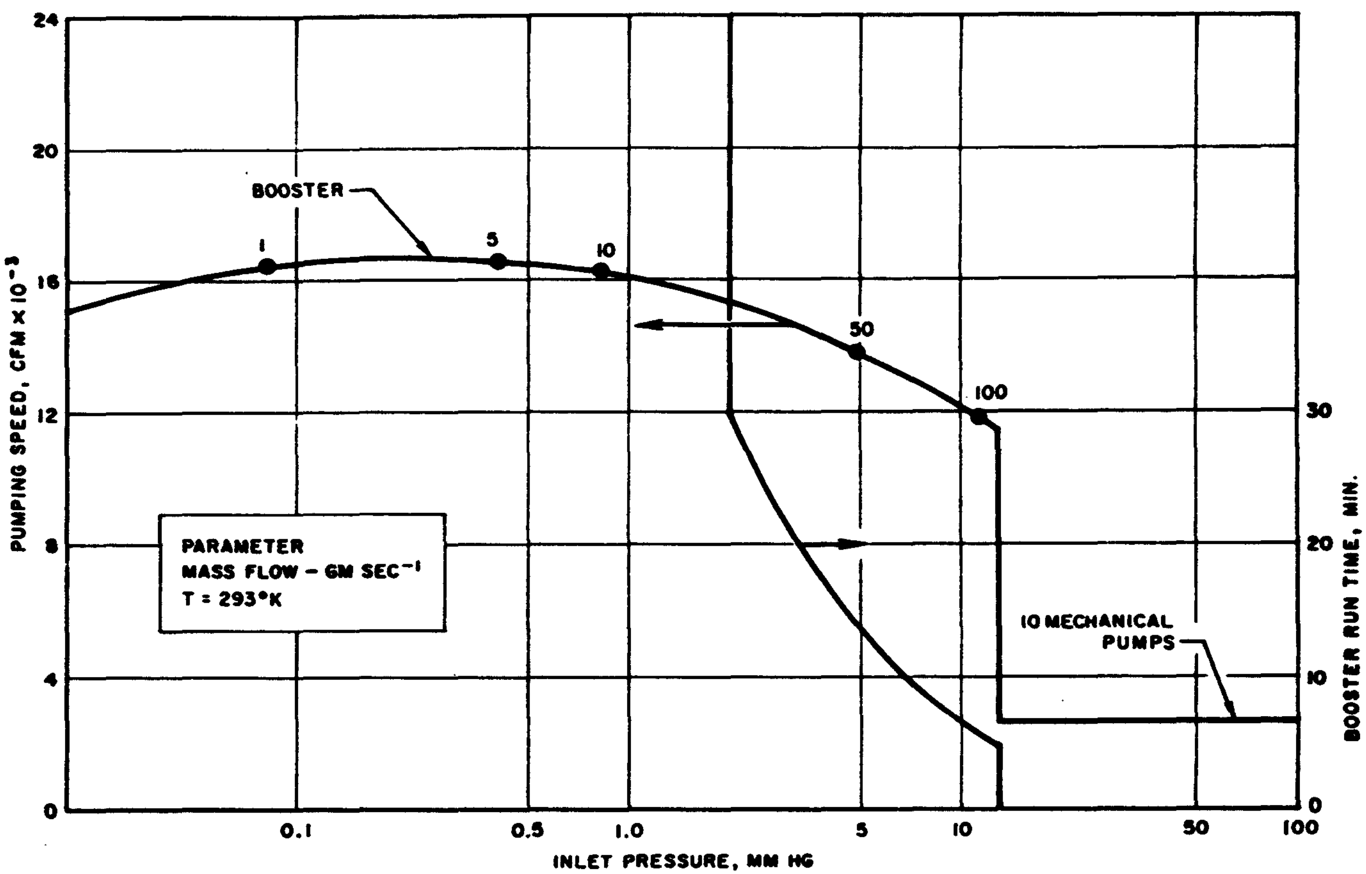

Figure III-3. Vacuum Pumping System Characteristics

max to 7 in. max), requiring a larger test section to reduce wall interaction with the plasma jet stream deflected by probes or models. (Probe and model installation will be more convenient in the larger test section.) The current test section would require water-cooling for safe operation during long duration testing. Therefore, a new test section has been designed to overcome deficiencies in the test section currently in use.

Because the jet stream must be carefully surveyed with probes (to obtain various local stream properties and to generate their radial profiles), an improved probe-support mechanism, with the capability of movement in two directions during tests, has been developed. All probes and models will be attached to this probe-support (pylon) mechanism.

The pylon configuration provides for dynamic vacuum sealing of the pylon at the test section wall; movement of the pylon within the test section will not affect the vacuum seal. The two directions of pylon motion are: (1) Radial - a motor-driven, continuous motion across the jet diameter for probe surveys, etc., or a pneumatically-driven sudden shift from a position near the wall to the jet axis (permitting rapid introduction of a model into the jet stream after plasma generator and instrumentation equilibrium have been attained); (2) Longitudinal - a motor-driven, continuous motion parallel to the jet axis for a distance up to 6 inches. (The radial survey velocity may range from 0.33 in/min to 10 in/min; the longitudinal advance velocity may be varied from 12 in/min to 365 in/min.) Thus, the mounted probes or models have two degrees of freedom, with respect to the plasma stream, for positioning or surveying. All other degrees of freedom are fixed when the model is secured to the pylon end.

C. TUNNEL CALIBRATION

1. Average Stagnation Enthalpy

Fabrication, instrumentation, and checkout of a total enthalpy calorimeter for use in the calibration of a subsonic arc jet facility were completed. This unit, designed by W. E. Welsh of this laboratory, consists of a bundle of 80

stainless steel tubes, 0.124 in. ID by 10 in. long, welded inside an 8 in. diam calorimeter jacket.

During operation, the space around the tubes is filled with water (approximately room temperature). The exhaust from the arc passes through the tubes where the gas is cooled to near water temperature. (Thermocouples measure the temperature rise of the coolant water and final exhaust temperature of the cooled gas.) The integrated stagnation enthalpy for a run is determined from knowing time of the run, gas mass flow, the heat absorption of the calorimeter, and the heat remaining in the exhaust gas. This procedure does not allow calibration of heat balance instrumentation at a given time after the run is initiated unless the jet enthalpy is constant during the run. Additional experimentation is required to determine the extent of enthalpy fluctuations during the run.

The calorimeter, as instrumented for checkout, is shown in Figure III-4. Preliminary calibration tests were performed on the calorimeter jacket and hardware to determine their heat absorbing capacity. Calorimeter checkout runs were performed at jet power levels of about 30 kw and H/RT_0 values of 160; run times varied from 20 to 60 sec. Water temperatures on top and bottom are equalized by a stirring motor. Final exit gas temperatures were within a few degrees of the water temperature (room temperature) level. Although the highest bulk water temperature attained was $120^{\circ}F$, local boiling was observed. For all runs of at least 30 sec duration, the integrated enthalpy was within 10 percent of the final reading of the electronic enthalpy computer.

2. Total Mass Flow

The mass flow rate of gas in the arc jet must be established before the more detailed diagnostic studies of the plasma can be undertaken. The 200 kw arc facility employs a revolving chart pen recorder in conjunction with subsonic flow orifices. This instrument was calibrated by imposing a pressure difference across the orifice tap lines and checking the readout against a

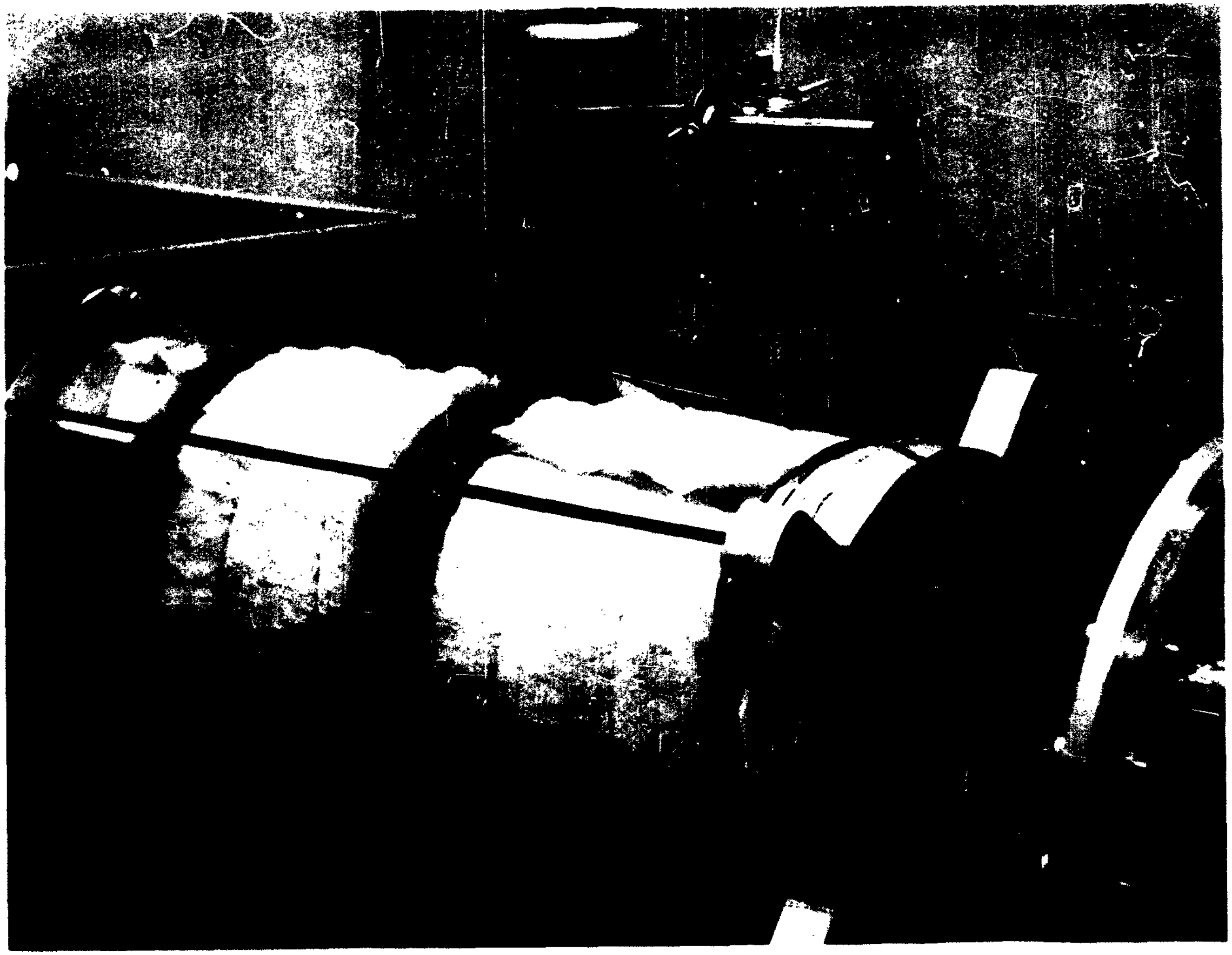

Figure III-4. Total Enthalpy Calorimeter

precision manometer. The orifice diameters were verified with a micrometer, and the systempressure level indicating penwas reset. A direct-reading flowmeter, with an accuracy of one percent of full scale reading, has been purchased for use as a standard of comparison to insure recording unit accuracy.

D. TUNNEL DIAGNOSTICS

1. Nozzle Flow Properties

a. Gross Flow Composition

A series of tests was completed in the 200 kw tunnel to determine the state of the gas during expansion to high Mach number. The supersonic nozzle with static pressure taps distributed along its length was utilized for these tests (Ref. III-1). This nozzle has a half angle of $7^{\circ}40'$, a throat diameter of 1.95 in., and an area ratio of 83. Average test conditions were $H/RT_0 = 175$ with a plenum pressure of 2 atm absolute and a tunnel pressure of 2 mm Hg.

Figure III-5 shows the pressure tap readings obtained with pressure transducers, plotted as a function of actual tap location (nozzle A/A*) and as corrected for boundary layer displacement thickness (Ref. III-2). The expansion curves for equilibrium flow and for various degrees of freezing are also shown (Ref. III-2, III-3); freezing was assumed to take place at the nozzle throat. The high tunnel and final nozzle pressure tap readings show that, due to the lack of pumping capacity, the nozzle was operated in an overexpanded condition. It is seen that the points plotted after boundary layer corrections show the "test core" in a nearly frozen condition.

b. Mach Number

The Mach number of the flow at the nozzle exit may be obtained from static pressure measurements if the size of the test core and state of the gas are known. Figure III-5 shows Mach numbers computed on this basis. This information may be obtained more directly by use of a water-cooled impact probe which measures the stagnation pressure behind a normal shock.

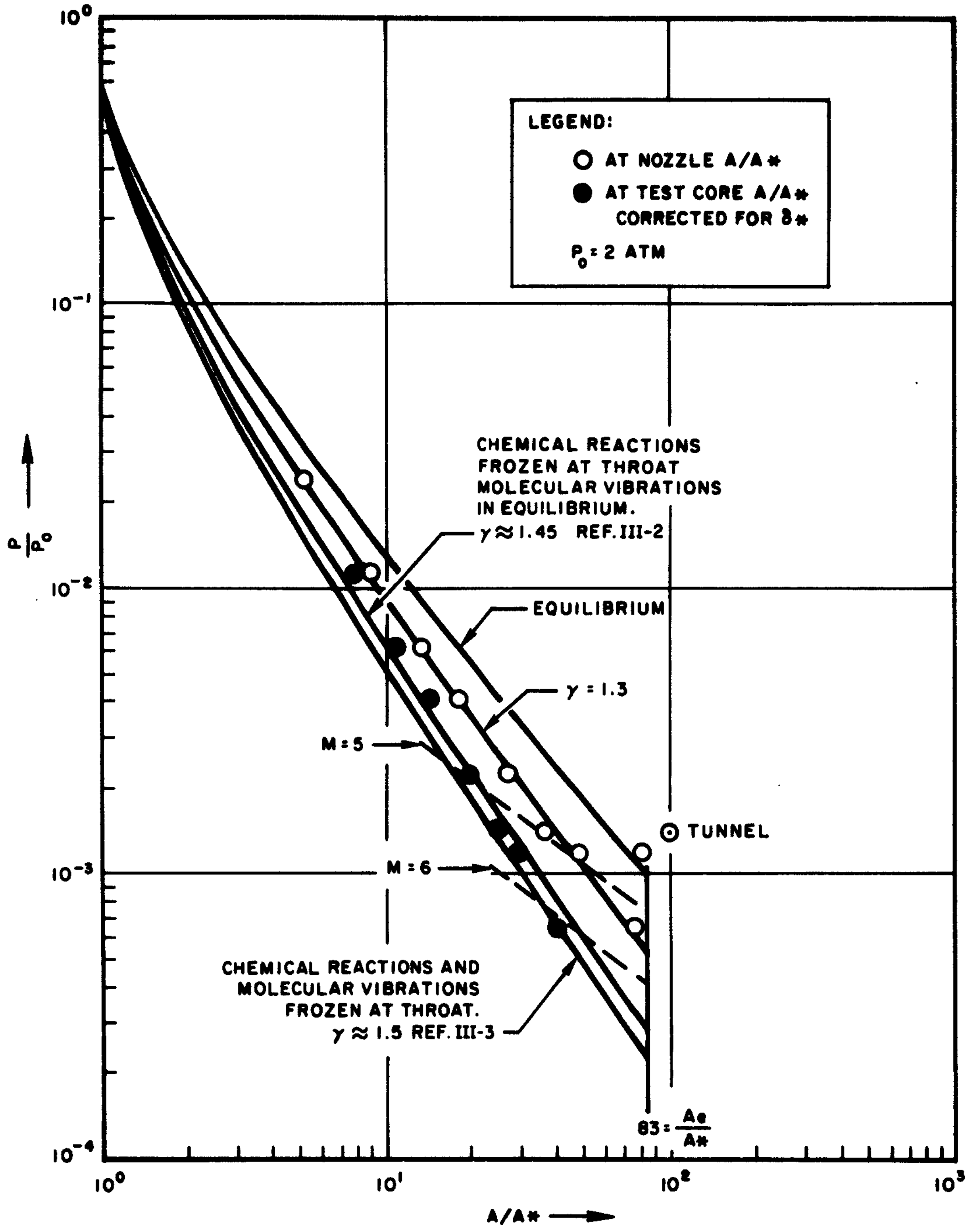

Figure III-5. Supersonic Nozzle Static Pressure Distribution

Figure III-6 shows a plot which allows determination of A/A* and γ from nozzle exit static pressure and impact probe results (Ref. III-4). In the construction of this plot, it was assumed that conventional one-dimensional normal shock relations are adequate. The Mach number can be calculated from the ratio P_{0y}/P_x once the state of the gas is known. It is shown that at the impact probe, $\gamma = 1.42$, which gives $M = 6.3$. This is in close agreement with the results shown in Figure III-5.

2. <u>Local Stagnation Enthalpy</u>

A water-cooled local enthalpy probe has been ordered from the Greyrad Corporation of Princeton, New Jersey, for use in traversing both subsonic and supersonic arc jets. Figure III-7 shows a cross section of the probe in operation. This particular probe utilizes a "tare" measurement which consists of measuring the temperature increase of the coolant water with and without a gas sample flow rate. In the "no-flow" condition, the device can be used as an impact probe. The rate of flow of sample gas must be so slight as to cause no significant change of conditions exterior to the probe.

Instrumentation required with this probe includes a high pressure water supply and metering system, a vacuum pump and flowmeter for gas sampling, and a thermocouple readout system. The probe is being built to specifications with a brass pylon which will adapt to the recently designed traversing mechanism.

E. TECHNICAL PLANS

Continuing research testing of materials will utilize the 200 kw tunnels the greater portion of the time. Partly in conjunction with these tests, and partly during otherwise unused tunnel time, diagnostic studies will continue to be performed on these arc exhaust streams to determine the average and local characteristics of temperature impact, pressure, enthalpy, and chemical and electrical composition. Future nozzle flow investigations will, in addition to present methods, utilize axially and radially traversed static and impact pressure probes and the recently purchased local enthalpy probe.

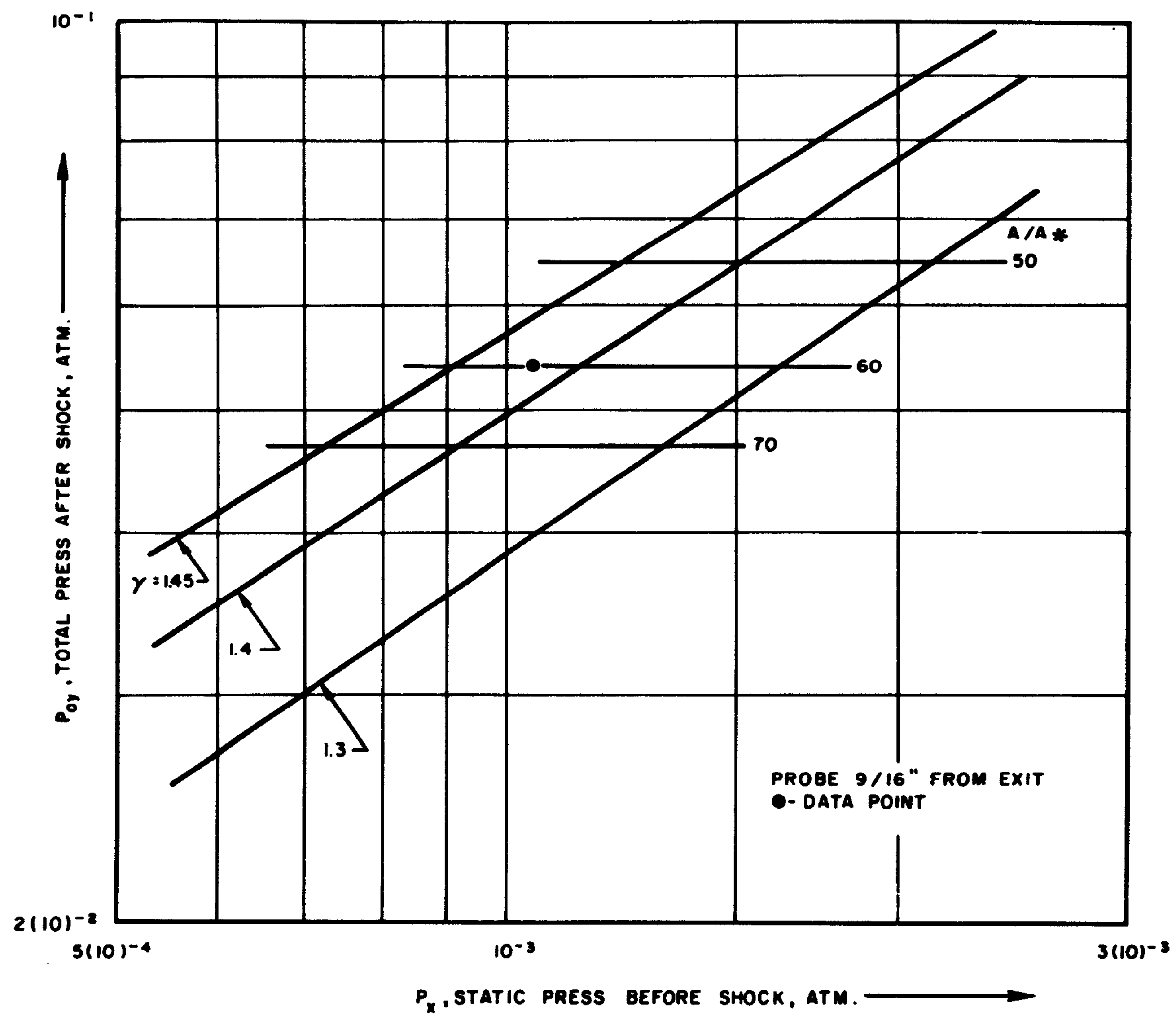

Figure III-6. Impact Probe Results

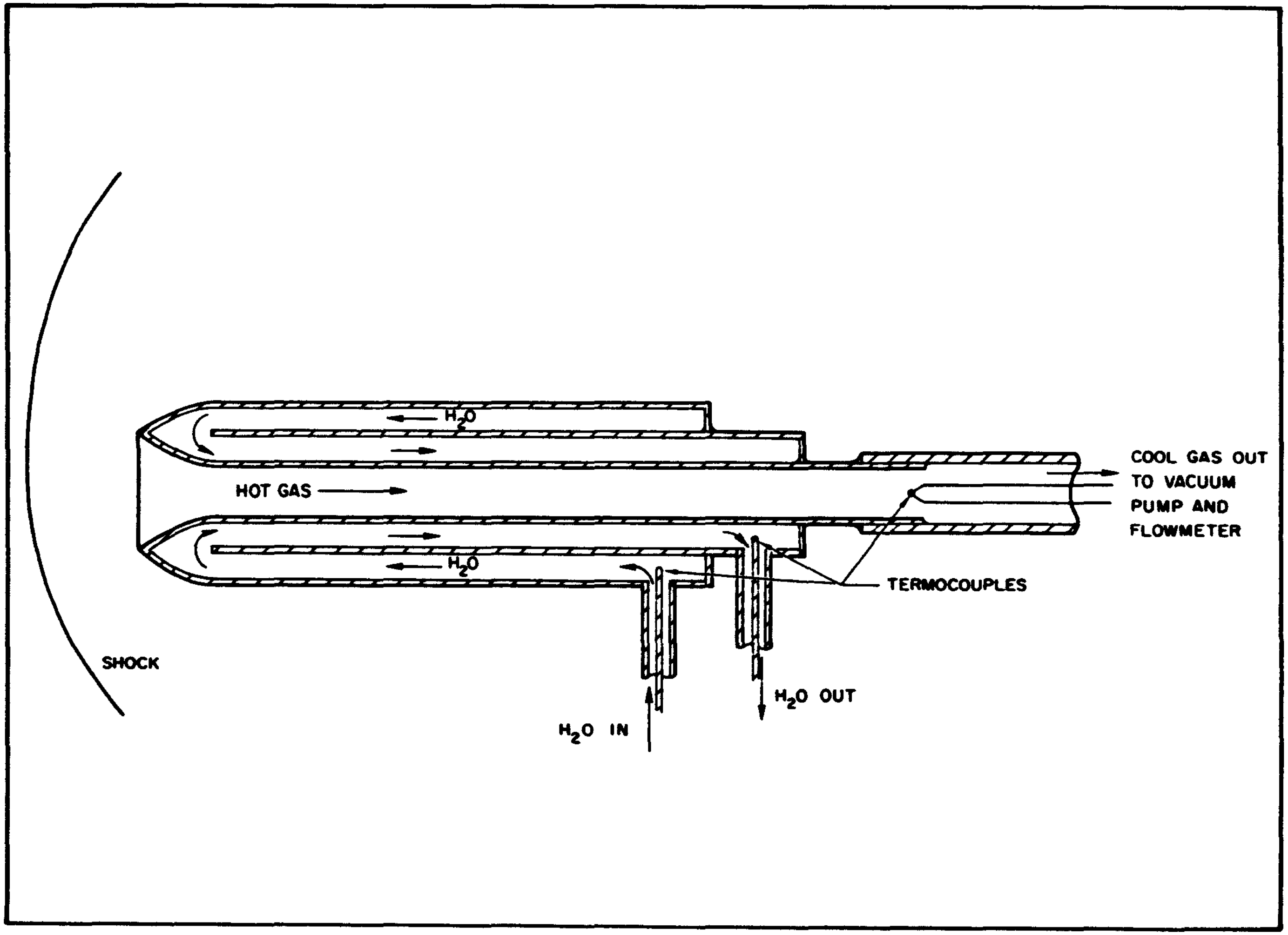

Figure III-7. Enthalpy Probe Cross Section

These tests will permit more exacting definition of test conditions to be imposed by the arc stream in future experiments.

Heat transfer tests utilizing the 2 Mw tunnel are planned for the near future. Tunnel time not used in these tests will be utilized in the performance of arc development studies. The goals of the arc generator development phase of this plan are the reduction of contaminants in the gas stream and the extension of the facility simulation domain. Achievement of these goals will involve complete checkout of the Gerdien arc unit and other novel designs.

The improved pumping capacity will provide the capability for good pressure matching of tunnel and nozzle. Improvement of arc heat balance instrumentation will continue, and periodic accuracy checks of all readout equipment will be continued. Upon completion of uncontaminated arc development, a program of Langmuir probe studies will be initiated to investigate gas kinetic and electrical parameters. To date, it has been felt that the high contamination level caused by cathode erosion would cause erroneous electrical probe results.

F. REFERENCES

III-1. Spencer, D. J., "Materials and Structures Program", Semiannual Technical Report, 1 July - 31 December 1961, TDR-930(2240-20)TR-1, p. 41, 28 February 1962.

III-2. Pearce, K., S. Samel, and R. J. Whalen, "Similarity Studies for Dissociating Gases in Hypersonic, Low Density Flow", WADD Technical Report 60-341, September 1960.

III-3. Yoshikawa, K. K. and E. D. Katzen, "Charts for Air-Flow Properties in Equilibrium and Frozen Flows in Hypervelocity Nozzles", NASA, TN D-693, April 1961.

III-4. Hayman, L. O., Jr., and R. B. Stewart, "A Technique for Determining the Nozzle-Flow Properties of Air in an Equilibrium, Nonequilibrium, or Frozen State", Journal of the Aero/Space Sciences, p. 245, February 1962.

Aerospace Corporation, El Segundo, California. HEAT TRANSFER AND FLUID MECHANICS, SEMIANNUAL TECHNICAL REPORT, 1 JULY - 31 DECEMBER 1962, prepared by P. M. Chung, W. S. Lewellen, and D. J. Spencer, 28 February 1963 [36]p. incl. illus. (Report TDR-169(3230-12)TR-2; SSD-TDR-63-44) (Contract AF 04(695)-169) Unclassified report This report covers the major areas of: Heat Transfer, Fluid Mechanics, and Arc Tunnel Facilities. Studies of the effect of various distributions of surface catalycity on heat transfer for frozen boundary layer flows of dissociated gas around hypersonic bodies are summarized. The fluid dynamics investigations include summaries of studies of expansion of gas clouds, three-dimensional boundary layers, electrical interactions of weakly ionized gas with solid boundaries, vortex flows, test time in shock tubes, and (over)	UNCLASSIFIED UNCLASSIFIED

Aerospace Corporation, El Segundo, California. HEAT TRANSFER AND FLUID MECHANICS, SEMIANNUAL TECHNICAL REPORT, 1 JULY - 31 DECEMBER 1962, prepared by P. M. Chung, W. S. Lewellen, and D. J. Spencer, 28 February 1963 [36]p. incl. illus. (Report TDR-169(3230-12)TR-2; SSD-TDR-63-44) (Contract AF 04(695)-169) Unclassified report This report covers the major areas of: Heat Transfer, Fluid Mechanics, and Arc Tunnel Facilities. Studies of the effect of various distributions of surface catalycity on heat transfer for frozen boundary layer flows of dissociated gas around hypersonic bodies are summarized. The fluid dynamics investigations include summaries of studies of expansion of gas clouds, three-dimensional boundary layers, electrical interactions of weakly ionized gas with solid boundaries, vortex flows, test time in shock tubes, and (over)	UNCLASSIFIED UNCLASSIFIED

Aerospace Corporation, El Segundo, California. HEAT TRANSFER AND FLUID MECHANICS, SEMIANNUAL TECHNICAL REPORT, 1 JULY - 31 DECEMBER 1962, prepared by P. M. Chung, W. S. Lewellen, and D. J. Spencer, 28 February 1963 [36]p. incl. illus. (Report TDR-169(3230-12)TR-2; SSD-TDR-63-44) (Contract AF 04(695)-169) Unclassified report This report covers the major areas of: Heat Transfer, Fluid Mechanics, and Arc Tunnel Facilities. Studies of the effect of various distributions of surface catalycity on heat transfer for frozen boundary layer flows of dissociated gas around hypersonic bodies are summarized. The fluid dynamics investigations include summaries of studies of expansion of gas clouds, three-dimensional boundary layers, electrical interactions of weakly ionized gas with solid boundaries, vortex flows, test time in shock tubes, and (over)	UNCLASSIFIED UNCLASSIFIED

Aerospace Corporation, El Segundo, California. HEAT TRANSFER AND FLUID MECHANICS, SEMIANNUAL TECHNICAL REPORT, 1 JULY - 31 DECEMBER 1962, prepared by P. M. Chung, W. S. Lewellen, and D. J. Spencer, 28 February 1963 [36]p. incl. illus. (Report TDR-169(3230-12)TR-2; SSD-TDR-63-44) (Contract AF 04(695)-169) Unclassified report This report covers the major areas of: Heat Transfer, Fluid Mechanics, and Arc Tunnel Facilities. Studies of the effect of various distributions of surface catalycity on heat transfer for frozen boundary layer flows of dissociated gas around hypersonic bodies are summarized. The fluid dynamics investigations include summaries of studies of expansion of gas clouds, three-dimensional boundary layers, electrical interactions of weakly ionized gas with solid boundaries, vortex flows, test time in shock tubes, and (over)	UNCLASSIFIED UNCLASSIFIED

UNCLASSIFIED

secondary injection for thrust vector control. Arc tunnel facility improvements include completion of the high capacity pumping system, implementation of the constant power control system, and design of an improved test section and model/probe support mechanism.

UNCLASSIFIED

UNCLASSIFIED

secondary injection for thrust vector control. Arc tunnel facility improvements include completion of the high capacity pumping system, implementation of the constant power control system, and design of an improved test section and model/probe support mechanism.

UNCLASSIFIED

UNCLASSIFIED

secondary injection for thrust vector control. Arc tunnel facility improvements include completion of the high capacity pumping system, implementation of the constant power control system, and design of an improved test section and model/probe support mechanism.

UNCLASSIFIED

UNCLASSIFIED

secondary injection for thrust vector control. Arc tunnel facility improvements include completion of the high capacity pumping system, implementation of the constant power control system, and design of an improved test section and model/probe support mechanism.

UNCLASSIFIED